

Gyrotron Power Beams for Defence Applications

by

Professor Chris Chatwin,

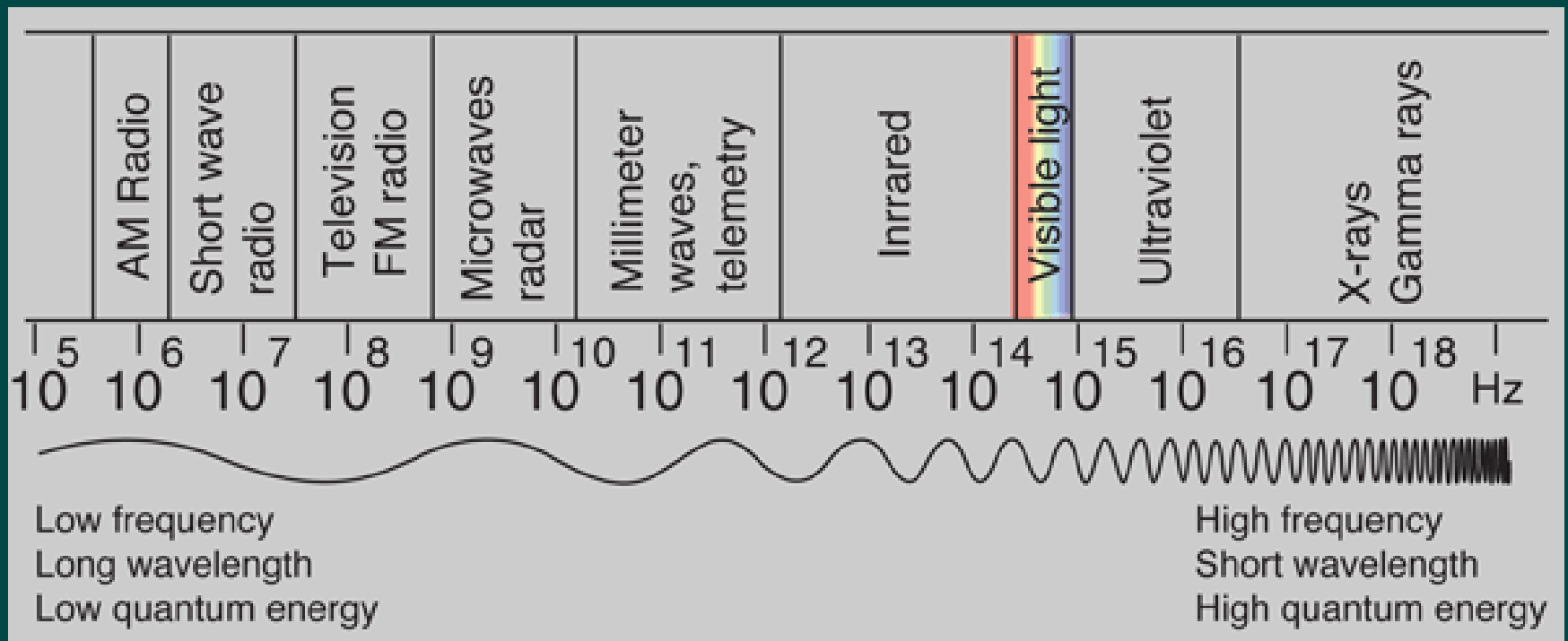
Dr Rupert Young, Dr Phil Birch

IET Colloquium – Lecture Theatre AS3 – Richmond Building, University of
Sussex

Brighton – 18th October 2016, 19:00 hrs

- Thermo-Mechanical Damage via Optical Power Beams
 - i. *US Navy Laser system – NRL 33kW fibre laser*
 - ii. *Lockheed Martin 30kW fibre laser*
- A millimetre approach and target vulnerabilities
- A Simple Gyrotron
- Some Gyrotron achievements
- Applications
- Conclusions

The Electromagnetic Spectrum



Thermal Mechanical Damage with Optical Beams

- In a previous presentation [1], I assessed Laser beam weapons that operate at optical frequencies
- There are two systems of note that can be used to damage and destroy a range of targets
 - i. *US Navy Laser Weapon System (LaWS) - NRL*
 - ii. *Lockheed Martin 30 kW system using Spectral beam combining*
- To blast a hole through the external skin of a target is hard work although damage to sensors and optics is effective

US Navy Laser Weapon System (LaWS) - NRL

- The US Navy's Laser Weapon System (LaWS) contains six individual fiber lasers with their beams incoherently combined into a single 33 kW output. (*Courtesy of US Navy*)



<http://www.laserfocusworld.com/articles/print/volume-48/issue-04/features/the-state-of-the-art.html>



Lockheed Martin 30 kW system using Spectral beam combining



Lockheed Martin 30 kW

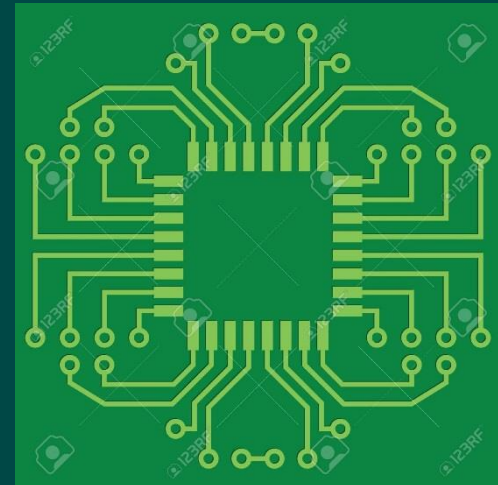
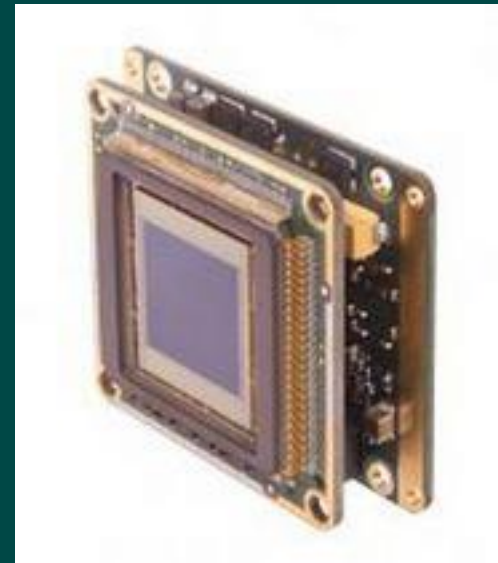
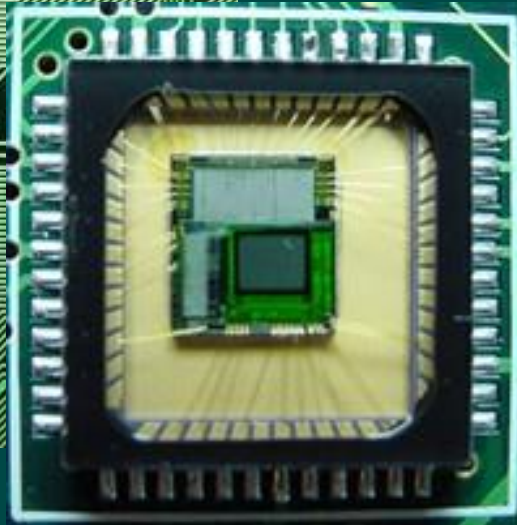
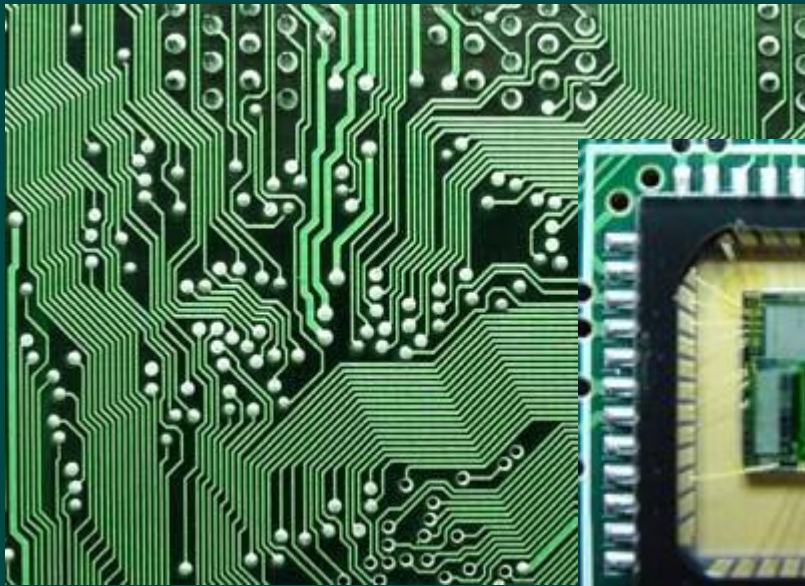
BETHESDA, Md., March 3, 2015 – Lockheed Martin's [NYSE: LMT] 30-kW fiber laser system successfully disabled the engine of a small truck during a recent field test, demonstrating the rapidly evolving precision capability to protect military forces and critical infrastructure.

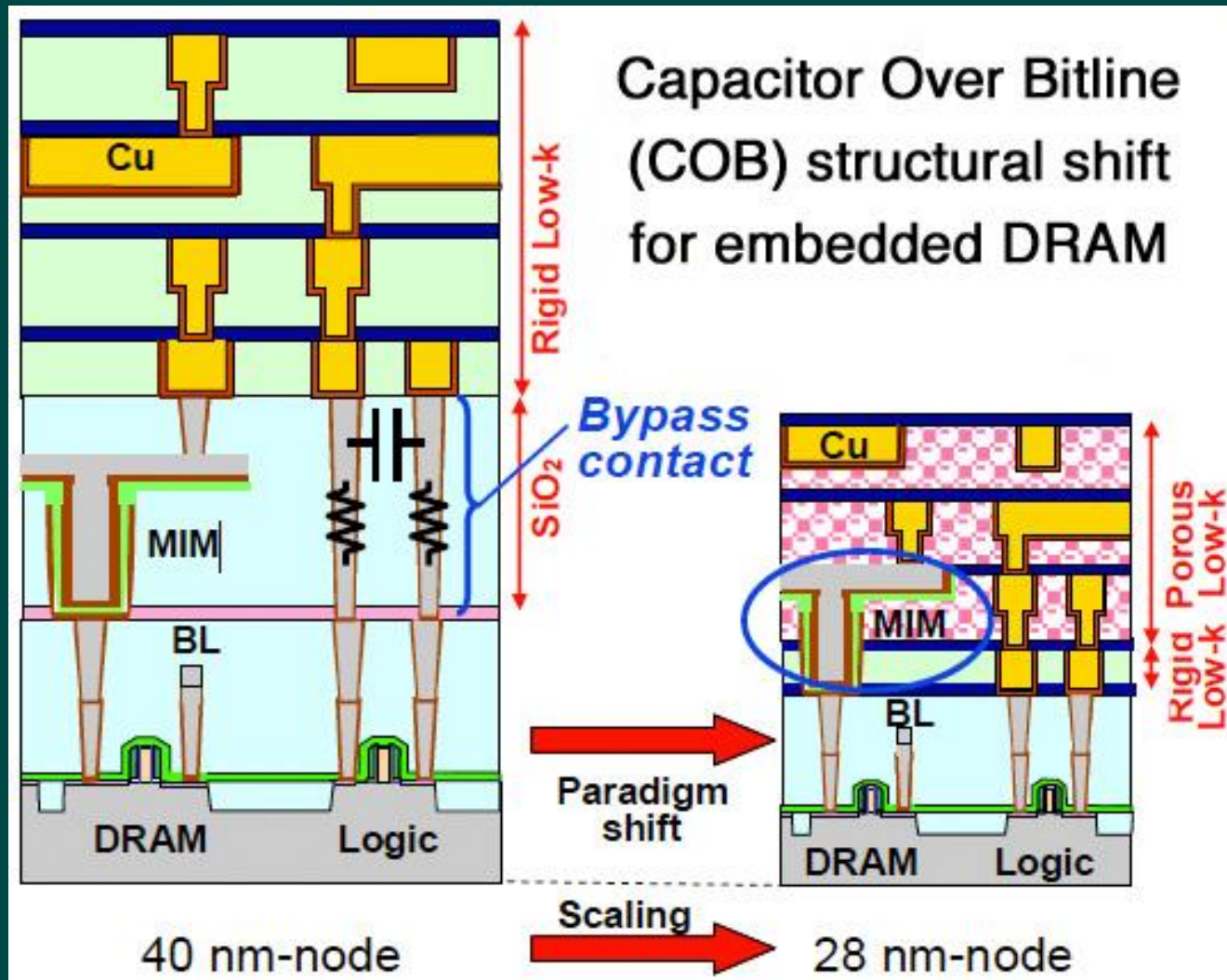
<http://www.sme.org/MEMagazine/Article.aspx?id=84571&taxid=3440#sthash.gn1DnEoL.dpuf>



- An alternative approach is to try to damage or destroy the targets' electronics or control systems
- Moving into the microwave part of the electromagnetic spectrum offers this opportunity
- Pulses of electromagnetic energy can produce large transient voltages on exposed electrical conductors, such as: wires, conductive tracks on electronic circuit boards, conductors in integrated electronics, semi conductor devices...

CMOS micro camera module (IR) & some circuit boards





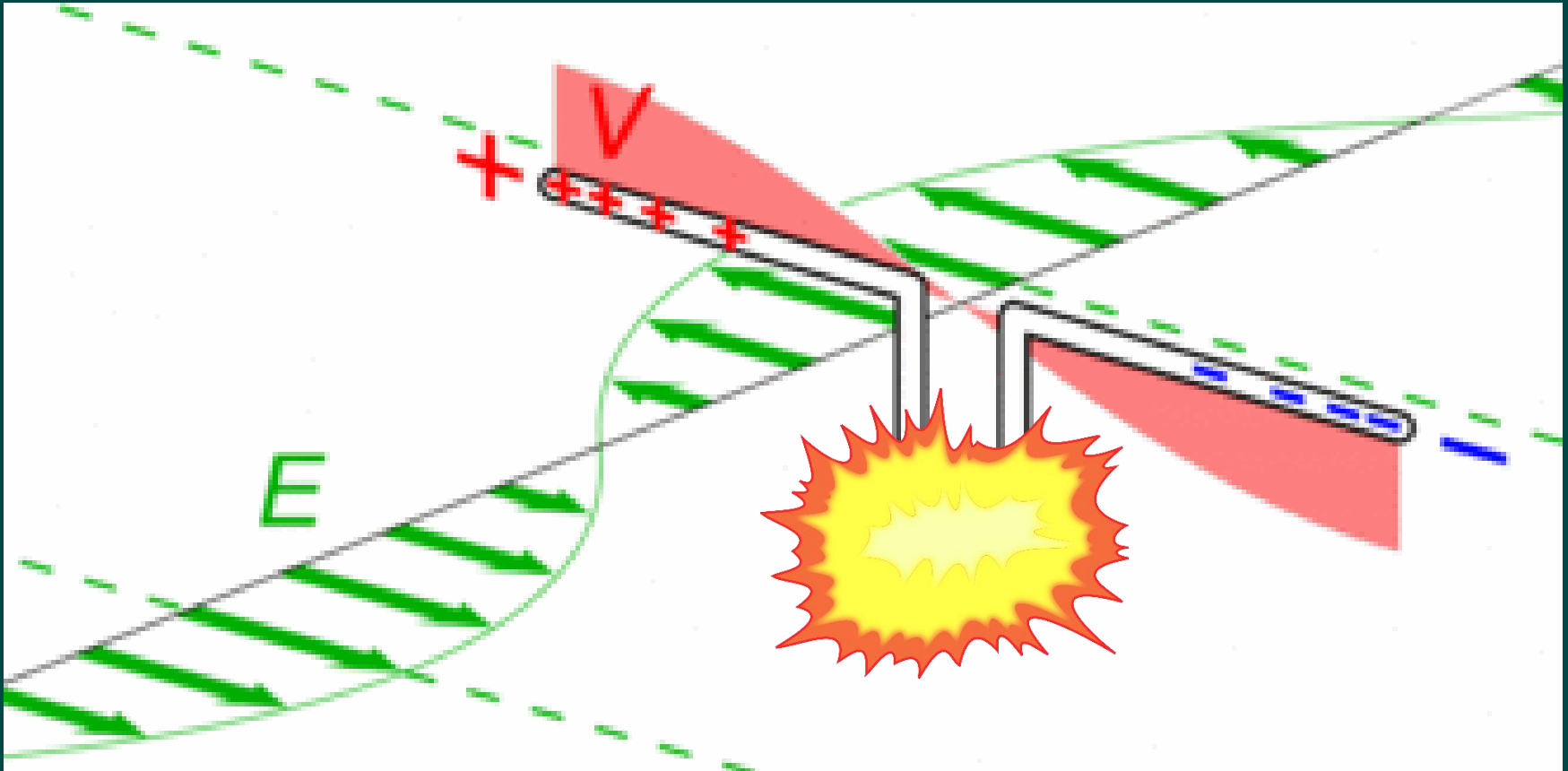
- Transient voltages may destroy or wound electronics, which will then perform erratically
- Semiconductor components using CMOS, RF Bipolar, RF GaAs, NMOS DRAM processes are destroyed by exposure to volts to tens of volts of electrical voltage
- Intermittent functionality can be more damaging than complete destruction
- Equipment with antenna's designed to conduct power into or out of a device are particularly vulnerable; this is called front door coupling



- Coupling is greatest when the wavelength of the pulse is close to the wavelength of the antenna or a multiple of the antenna's length
- UHF and VHF radio receivers, televisions and cell phones are all vulnerable to front door coupling
- Radar systems (destroys RF semiconductor devices) and measurement instrumentation used for control of target machines, GPS receivers are all vulnerable

Antenna animation, front door coupling

(Courtesy Chetvorno CC)



Animated diagram of a half-wave dipole antenna receiving energy from a radio wave. Each rod is one quarter of the wavelength long. Black arrows are the electrons moving back and forth in the rods, this excites standing waves of voltage shown in red.

Radar-frequency bands according to IEEE standard

Radar-frequency bands according to IEEE standard		
Band designation	Frequency range	
<u>HF</u>	0.003 to 0.03 GHz	High Frequency ^[7]
<u>VHF</u>	0.03 to 0.3 GHz	Very High Frequency ^[7]
<u>UHF</u>	0.3 to 1 GHz	Ultra High Frequency ^[7]
<u>L</u>	1 to 2 GHz GPS	Long wave
<u>S</u>	2 to 4 GHz	Short wave
<u>C</u>	4 to 8 GHz	Compromise between S and X
<u>X</u>	8 to 12 GHz	Used in <u>WW II</u> for <u>fire control</u> , X for cross (as in <u>crosshair</u>). Exotic. ^[8]
<u>Ku</u>	12 to 18 GHz	Kurz-under
<u>K</u>	18 to 27 GHz	<u>German</u> Kurz (short)
<u>Ka</u>	27 to 40 GHz	Kurz-above
<u>V</u>	40 to 75 GHz	
<u>W</u>	75 to 110 GHz	W follows V in the <u>alphabet</u>
<u>mm</u> or <u>G</u>	110 to 300 GHz ^[note 1]	Millimeter ^[6]

Predator - Unmanned Aerial Vehicle (UAV) – Numerous Front Doors



UHF and VHF radio relay links, a C-band line-of-sight data link which has a range of 150nm and UHF and Ku-band satellite data links.

The vehicle carries electro-optical and infrared cameras and a synthetic aperture radar.

The two-colour DLTV television is equipped with a variable zoom and 955mm Spotter. The high resolution FLIR has six fields of view, 19mm to 560mm.

Global Hawk High-Altitude, Long-Endurance, Unmanned Reconnaissance Aircraft, USA – **Many** **Front Door access points**



Performance:

**Maximum Endurance: 42
hours**

Loiter Velocity = 343kt

Maximum Altitude: 65,000ft

Communications:

**Satellite Comms Datalink
1.5Mbps, 8.67Mbps, 20Mbps,**

30Mbps, 40Mbps, 47.9Mbps

**Line of Sight (LOS) Datalink
137Mbps**

Synthetic Aperture Radar (SAR) - 1m/0.3m resolution (WAS / Spot)

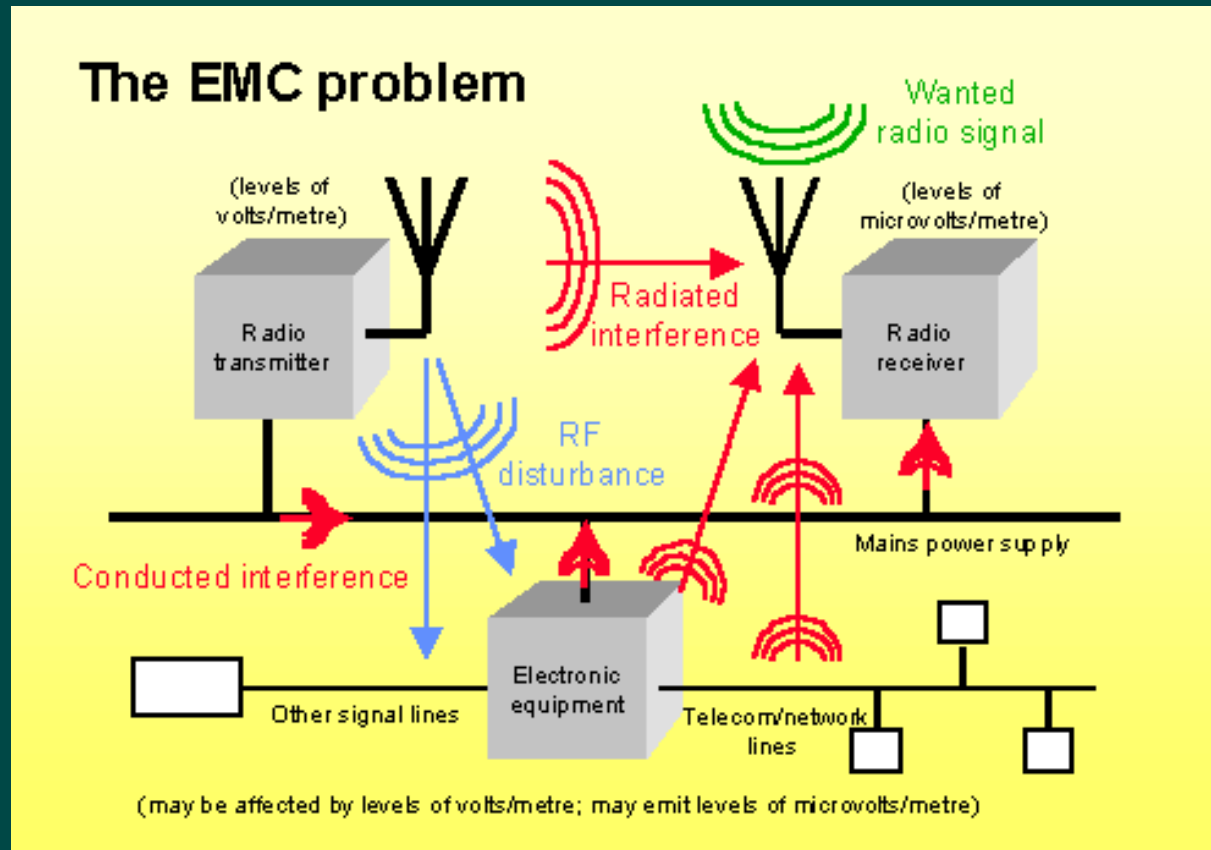
Moving Target Indicator - 4kt minimum detectable velocity

Electro-Optical - NIIRS 5.5 / 6.5 (WAS/Spot)

Infrared - NIIRS 5.0 / 6.0 (WAS/Spot)

Gyrotrons offer an important defensive opportunity

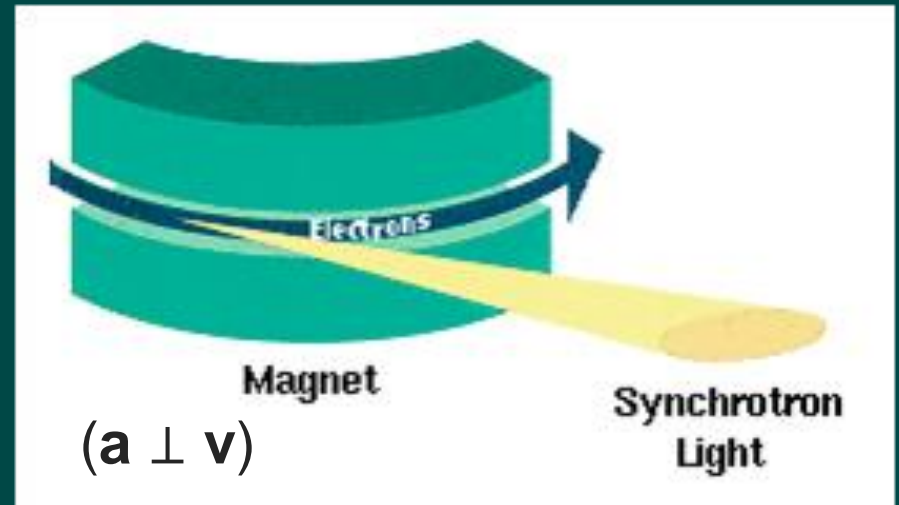
- Gyrotrons can be deployed for significant defence applications.
- Gyrotrons offer an efficient low cost source of extremely high power millimetre electromagnetic radiation
- The first gyrotron was invented, designed and tested in Gorky, USSR (now Nizhny Novgorod, Russia), in 1964.



- The diagram illustrates how radio transmitters can interfere with electronic systems, and how electronic systems can interfere with radio reception. For damage you just need to make the interference very large

Synchrotron radiation

The acceleration of ultra-relativistic charged particles through magnetic fields results in synchrotron radiation



Single Cavity Gyrotron ^[20, 22]

According to the definition given in [21], gyrotrons are **cyclotron resonance masers (CRMs)** in which the interaction of helical electron beams with electromagnetic waves takes place in nearly uniform waveguides near their cut-off frequencies, where the '**B**' field is a maximum

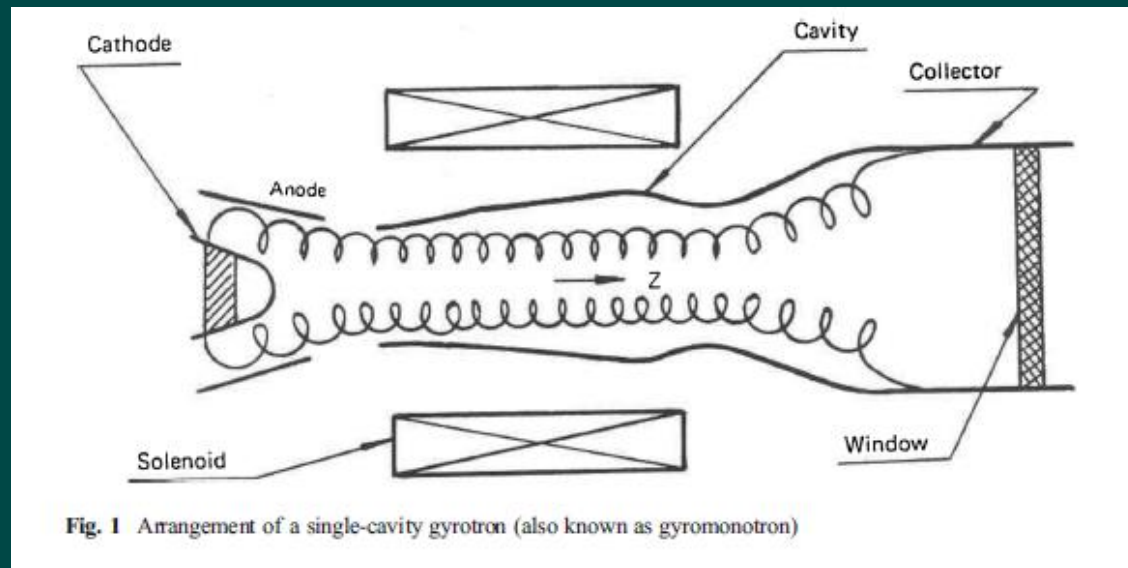
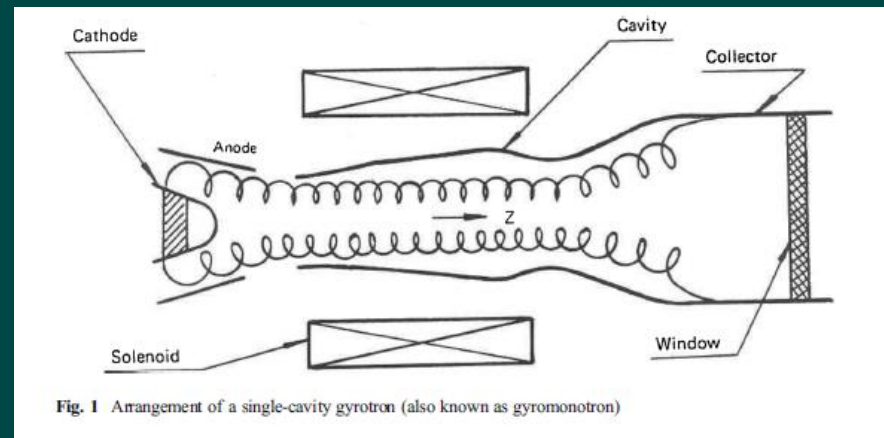


Fig. 1 Arrangement of a single-cavity gyrotron (also known as gyromonotron)

See Figure (1) opposite, the simplest gyrotron is known as a **gyromonotron** (it is a vacuum electronic tube)

Single Cavity Gyrotron

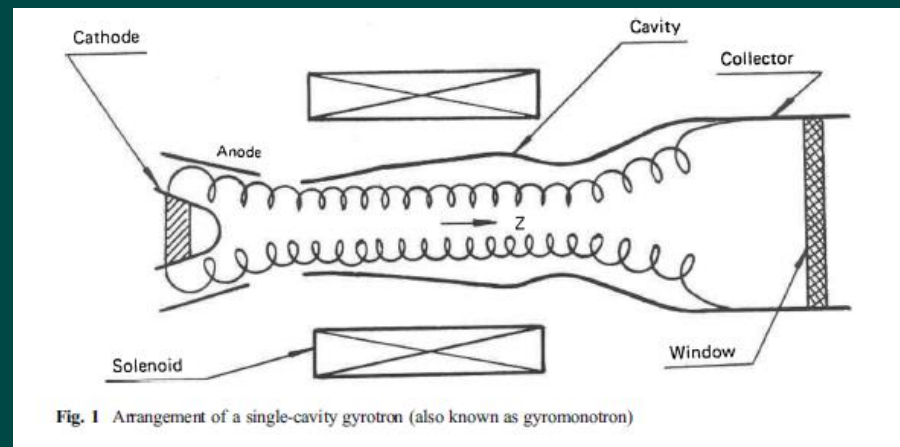
- A hollow electron beam is emitted from the cathode ring of the magnetron injection gun in the DC electric field caused by the voltage applied between the cathode and the anode.
- The electrons move towards the cavity in the increasing magnetic field 'B', thus experiencing an adiabatic compression which increases their transverse (orbital) momentum ' p ' in accordance with the conservation law $p_{\perp}^2 / B = \text{const.}$
- The axial magnetic field 'B' causes the electrons to rotate in a tight helical trajectory around the field lines



- In the cavity, electrons gyrating with the cyclotron frequency $\Omega = eB/m_0\gamma$ interact with the electromagnetic field (EM), under the cyclotron resonance condition (1), where e is the elementary charge, 'B' is the magnetic field, m_0 electron rest mass, $\gamma = 1/\{\sqrt{1 - (v/c)^2}\}$
- $\omega - k_z v_z \approx s\Omega \dots \dots \dots (1)$
- ω and k_z are the EM wave angular frequency and axial wavenumber, v_z is the electron axial velocity and s is the cyclotron resonance harmonic number ($s=1, 2, \dots$).

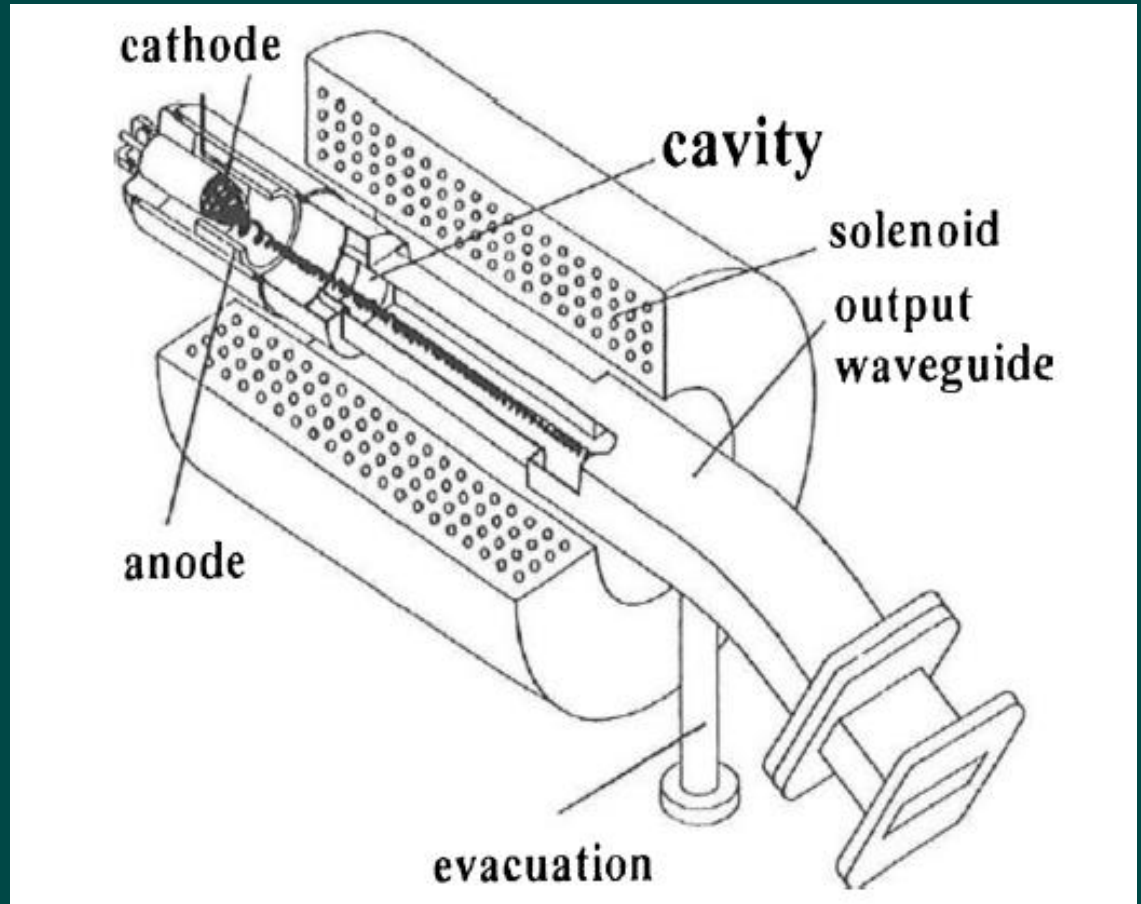
Single Cavity Gyrotron

- The spent electron beam moves in the decreasing magnetic field experiencing adiabatic decompression and reaches the collector
- The EM field excited in the cavity radiates through an open end into an up-tapered output waveguide and propagates through the output window
- The frequency of the output can be controlled by the strength of the magnetic field 'B'.



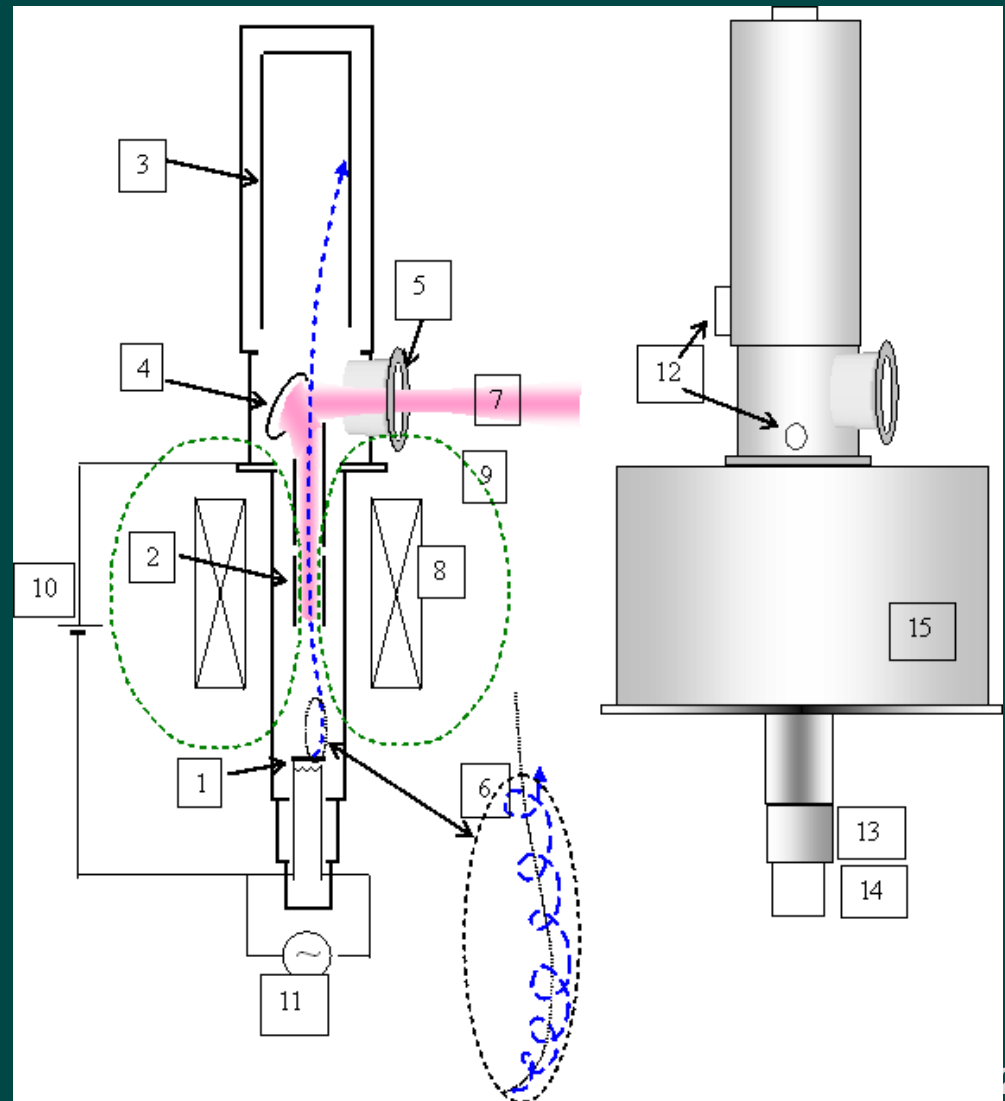
Layout of the first Gyrotron

Results of the first experiments with this device (6 W of the CW power at the fundamental cyclotronresonance in the X-band) were reported at the All-Union Electronics Conference in Moscow (1964)

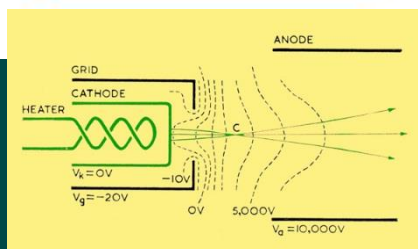
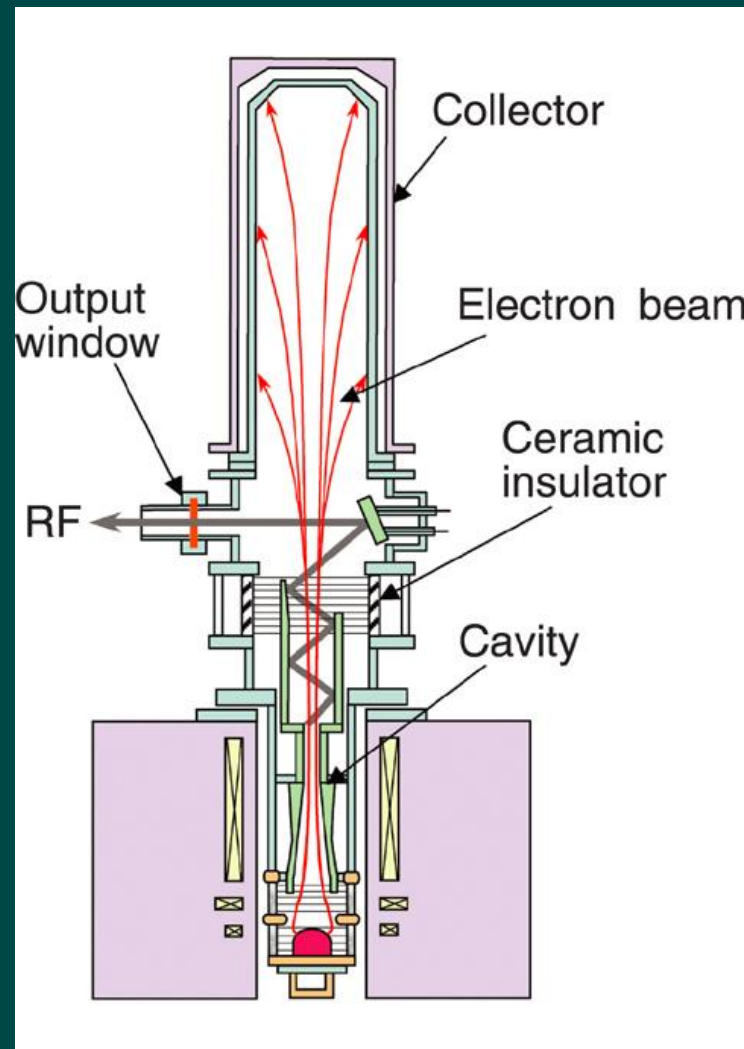
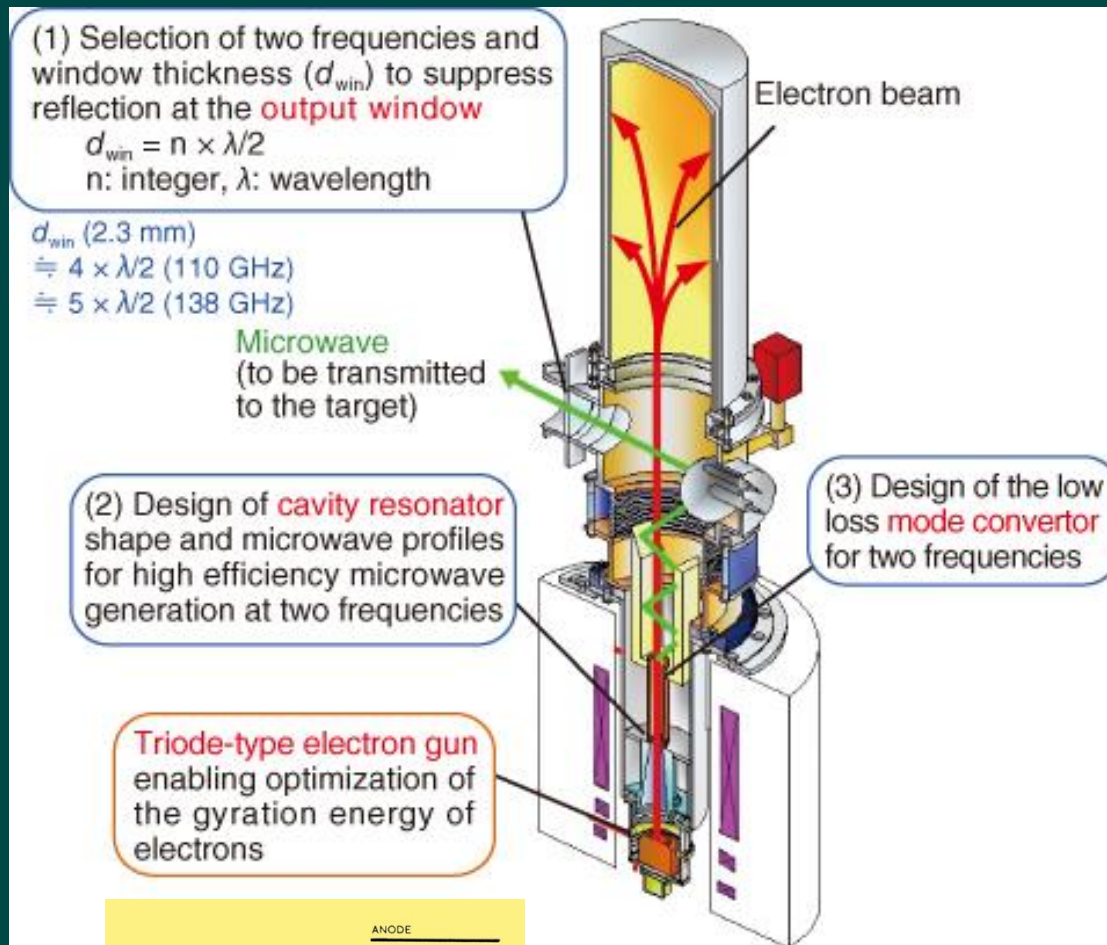


Gyrotron Schematic (fast wave device)

1. cathode with filament,
2. resonance cavity,
3. collector,
4. microwave mirror,
5. synthetic diamond vacuum window,
6. electron beam,
7. microwave beam,
8. magnet coils,
9. magnetic field,
10. high voltage power supply,
11. filament power supply,
12. cooling water connections,
13. electrical insulator,
14. high-voltage terminals,
15. magnet (possibly superconducting)



Dual-frequency Gyrotron [25]



- Gyrotrons – are capable of producing extremely high power beams of pulsed and CW electromagnetic radiation in the GHz and THz part of the spectrum. (2 GHz to 1.3 THz)
- They are actively being developed for fusion reactors. In Germany they are developing a 2MW, 170 GHz facility.

- Present state-of-the-art gyrotrons are used for controlled thermonuclear fusion plasma applications.
- They are mainly used as high power millimeter wave sources for:
 - i. *electron cyclotron resonance heating (ECRH),*
 - ii. *electron cyclotron current drive (ECCD),*
 - iii. *stability control and diagnostics of magnetically confined plasmas for generation of energy*

State of the Art Gyrotrons for fusion plasma applications

- Industrial megawatt-class CW gyrotrons that operate at 77GHz (LHD), 110 GHz and 138 GHz (DIII-D, JT-60SA), 140 GHz (W7-X), 154 GHz (LHD), and 170 GHz (ITER) for fusion plasma applications are available in Japan, USA, EU and Russia.
- The maximum pulse length of the 140 GHz, megawatt-class gyrotrons is 30 minutes
- The world record parameters of the European 140 GHz gyrotron are: 0.92 MW output power in 30 min. pulses, 97.5% Gaussian mode purity and 44% efficiency.

- A maximum output power of 1.5 MW in 4.0s pulses at 45% efficiency was generated with the JAEA-TOSHIBA 110 GHz gyrotron.
- The Japanese 170 GHz ITER gyrotron achieved 1 MW, 800s at 55% efficiency and holds the energy world record of 2.88 GJ (0.8 MW, 60 min.) and the efficiency record of 57% for tubes with an output power of more than 0.5 MW.
- The Russian 170GHz ITER gyrotron delivers 1 MW in 1000s pulses with 55% efficiency.

Megawatt-class long-pulse cylindrical cavity gyrotrons for ITER (170 GHz) and W7-X (140 GHz) ^[20]



ITER: TOSHIBA/JAEA (JA)



ITER: GYCOM/IAP (RF)

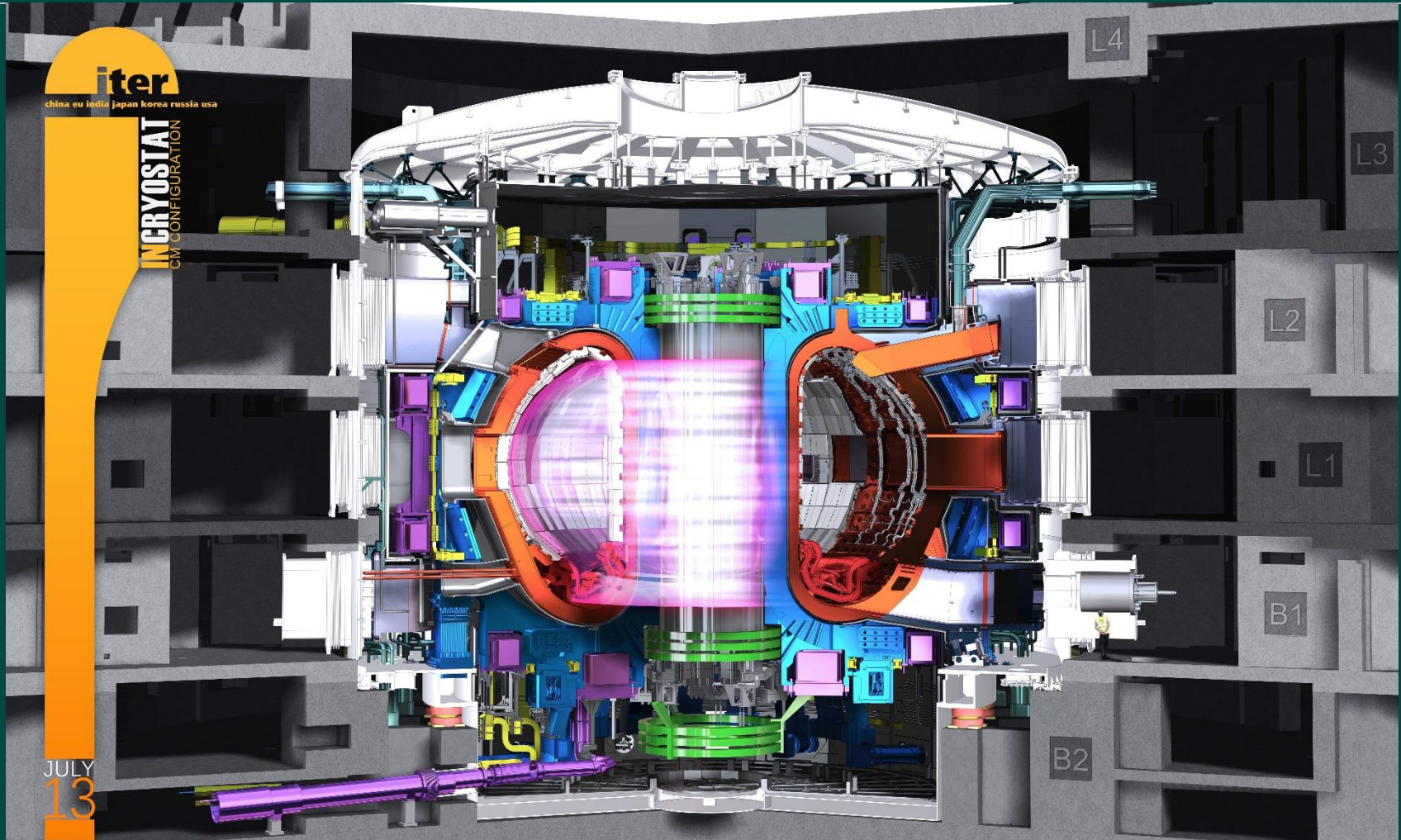


W7-X: CPI (USA)



W7-X: TED/KIT/CRPP (EU)

Iter Tokamak – plasma by 2025

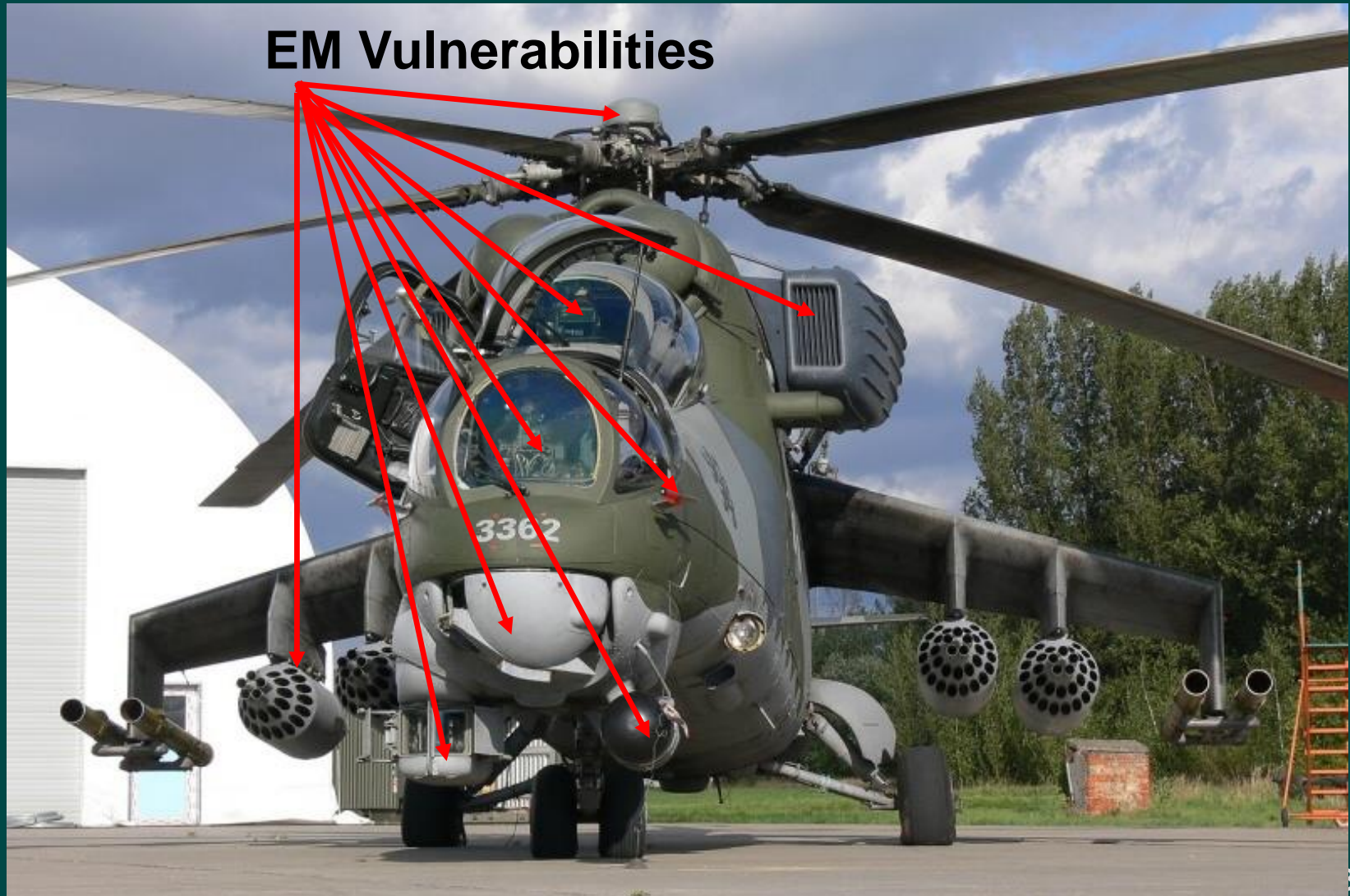


ITER ("The Way" in Latin)

- A system based on frequency step-tunable sources with frequency steps of 2-3 GHz could be used together with simple, fixed launcher structures without loss of performance. [20]
- Gyrotrons with ultra-broadband CVD-diamond windows and fast-tunable superconducting gyrotron magnets (sweeping speed 0.2 T/5s corresponding to 1GHz/s) would allow stepwise frequency tuning in the seconds time-scale in the full D-band (110-170 GHz)

- For the defence application short pulses are desirable, so design optimisation should aim at short high power pulses
- Chirping allows coupling into any in-band resonances
- Circular polarisation of antenna allows coupling with any aperture orientation

Mil Mi-24 (Russian: Миль Ми-24; NATO reporting name: Hind)



The RS-24 Yars is an upgraded
Russian intercontinental ballistic missile



Battle EMP generator Satchel-E (Russia)

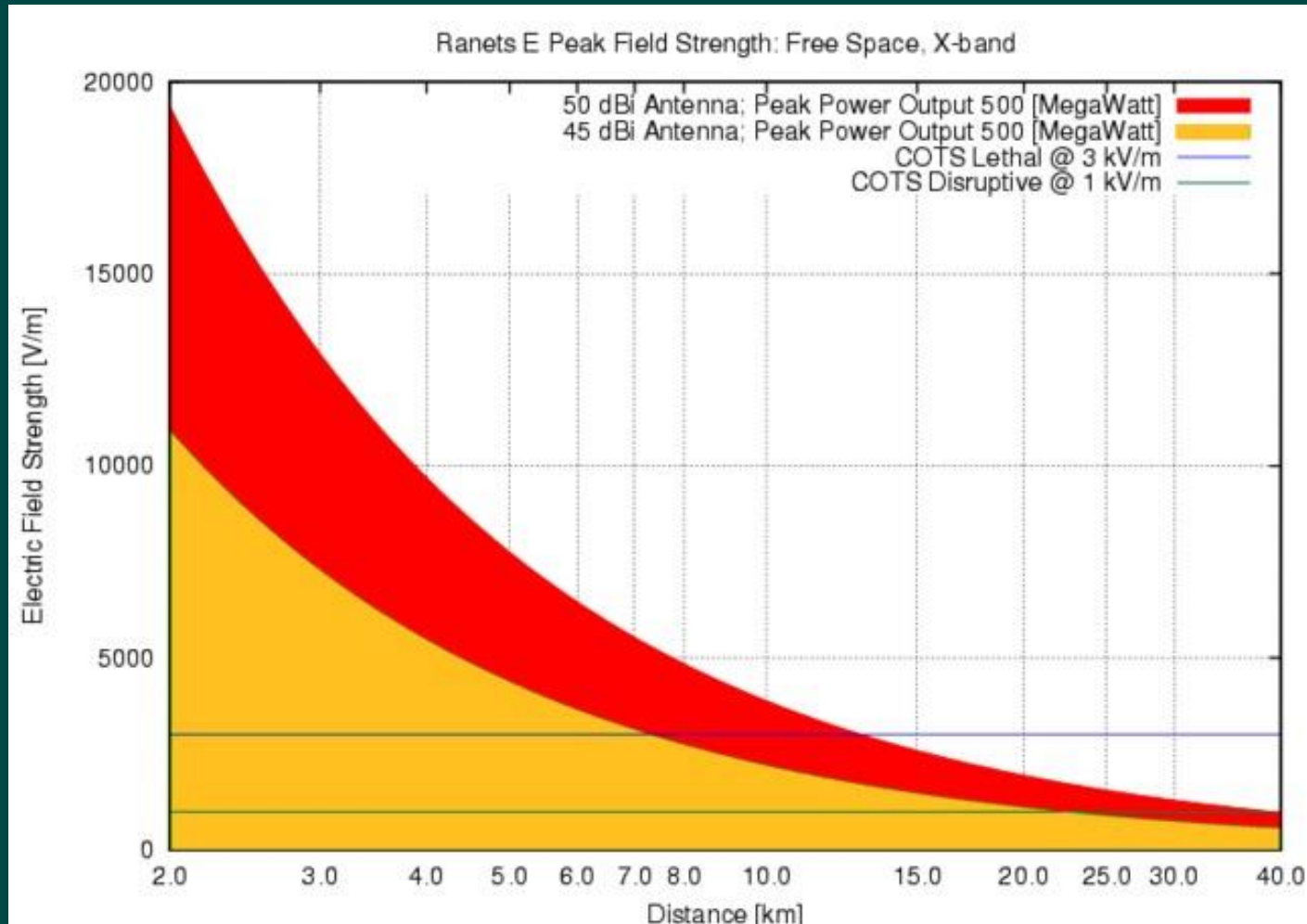
Output pulse duration
of 10-20 ns in the
centimeter wavelength
range exceeding 500
MW

It will strike guidance
systems and electronic
precision-guided
munitions and missiles
at a distance of 10 km
in a 60-degree sector,
also UAV's.



Serious disruption of navigation systems that
threaten the performance of combat missions, can be
observed at a distance of 40 kilometers

EMP generator Satchel-E



X Band
8 to 12 GHz

The system creates on the surface of the target kV/m, which causes breakouts, disabling the electronics

RANETS-E (Russia)



Daily Mirror 14th Oct 2016 – “Terrifying footage of Russia's 'world first' death-ray weapon that uses microwaves to fry enemy drones” [23]

“Instead of using rounds of bullets or shells to destroy enemy targets, this new weapon, which can be seen in this video, will use directed microwave energy This terrifying footage shows what Russia is claiming is the world's first weapon to use microwave energy 'death-rays' to target military drones.”



<http://www.mirror.co.uk/tech/russia-unveils-worlds-first-death-9043360>

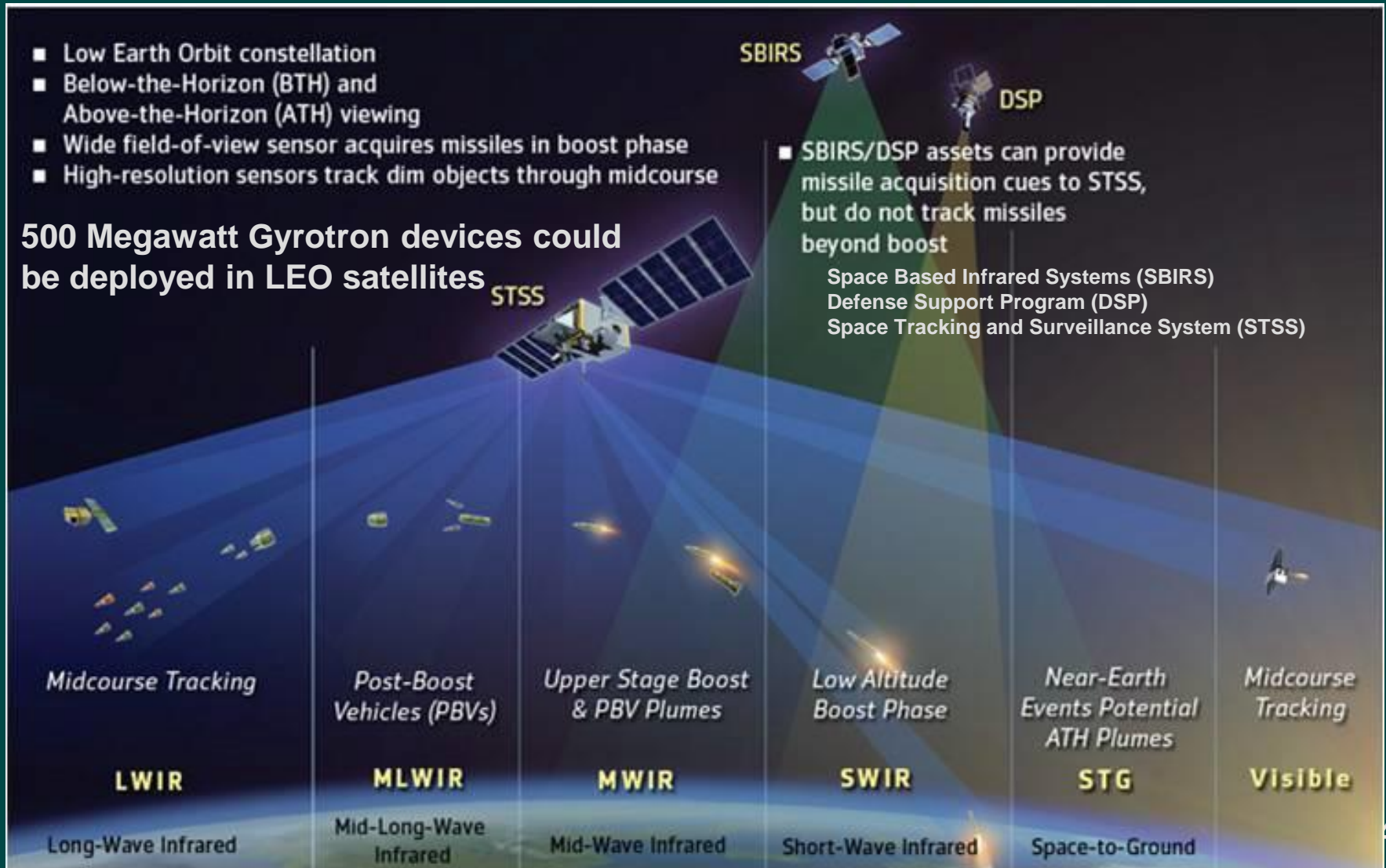
Igor Korotchenko, a chief officer in the National Defence, said: "We are talking about a prototype." He said that the weapon can aim "microwave pulses at powerful enemy targets with the aim of disabling their electronic equipment, which leads to a complete loss of functionality. "The most promising one for combat use can be disabling enemy tactical drones directly over the battlefield."



Integrated Detection Systems

- Low Earth Orbit constellation
- Below-the-Horizon (BTH) and Above-the-Horizon (ATH) viewing
- Wide field-of-view sensor acquires missiles in boost phase
- High-resolution sensors track dim objects through midcourse

500 Megawatt Gyrotron devices could be deployed in LEO satellites



500 MW Pulsed, Chirped, Circular
Polarisation, Gyrotrons in action, 60% energy
efficiency



Some Conclusions

- Gyrotrons are capable of producing Megawatt power radiation at millimeter and submillimeter wavelengths
- Gyrotrons are very efficient, circa 60%
- Gyrotrons can be made to chirp over wide frequency ranges
- Gyrotrons offer a very effective means of defence against advanced weaponry that relies on embedded electronics and multiple communication systems
- Electronics, sensors and communication systems can be damaged from a distance of 40 km
- The ability to deliver directed beams is straightforward
- Russia already has this technology to target Drones

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- 3) PHILLIP SPRANGLE, BAHMAN HAFIZI,* ANTONIO TING, AND RICHARD FISCHER, High-power lasers for directed-energy Applications, Vol. 54, No. 31 / November 1 2015 / Applied Optics
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The End

Gyrotron Schematics

- 1 - Cathode
- 2 - Gun coil magnets
- 3 - **Electron beam**
- 4 - Main magnet
- 5 - Cavity region
- 6 - Mode converter
- 7 - Collector
- 8 - Window
- 9 - **THz radiation**

